Tracking simulations of a higher-harmonic cavity for the APS upgrade

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Outline

- Why a higher harmonic cavity?
- APS-U nominal fill modes
- Modeling methods
- Bunch duration and shapes
- Touschek lifetime
- Intrabeam scattering
- Operational details
  - Effects of bunch population variation
  - Effects of loss of a bunch
  - Filling from zero
- Hybrid mode and other options
- Conclusion and plans

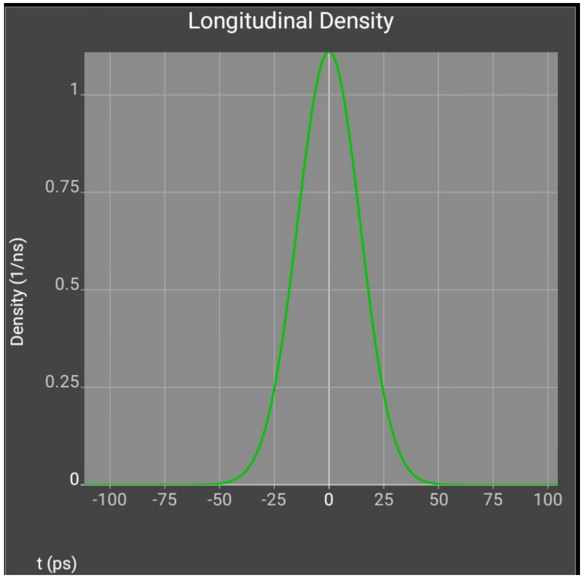
Why a higher-harmonic cavity?

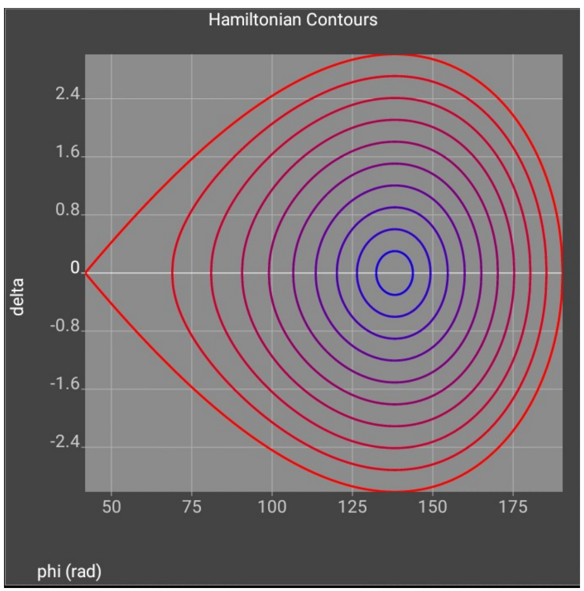
- New lattice has ultra-low emittance
  - 67 pm compared to 3100 pm today
- Users still want to perform timing experiments
  - I.e., we need intense single bunches
- Beam scattering phenomena become much more severe
  - Intra-beam scattering (IBS)
    - Multiple electron-electron scattering within a bunch
    - Causes emittance and energy spread growth
  - Touschek scattering
    - Hard electron-electron scattering within a bunch
    - Leads to electron loss and reduced beam lifetime
- Harmonic cavity can stretch the bunch longitudinally
  - Reduces electron density and collision rates
  - Improves emittance, energy spread, and lifetime

Planned APS-U fill and operating modes

- Minimum beam current of 200 mA
- Two fill patterns being advertised
  - 324-bunch uniform
    - Limit of present kicker technology
    - Desirable for long lifetime and possible flat beam operation
  - 48-bunch uniform
    - Desirable for timing experiments
    - Round beam operation required for lifetime reasons
    - Touschek lifetime and IBS particular an issue for this pattern
- Possible hybrid or non-uniform modes under study
  - Use of HHC impacts these modes in interesting ways
- Swap-out injection
  - Single bunch swapping only
  - 5-15 s interval

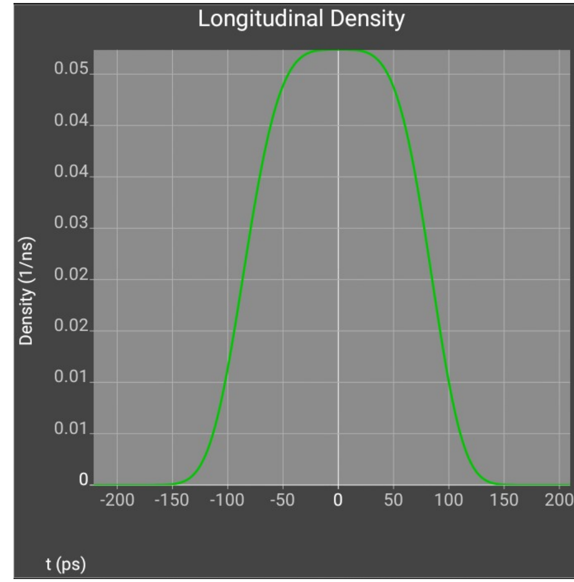
Expected effect of HHC in APS MBA Lattice

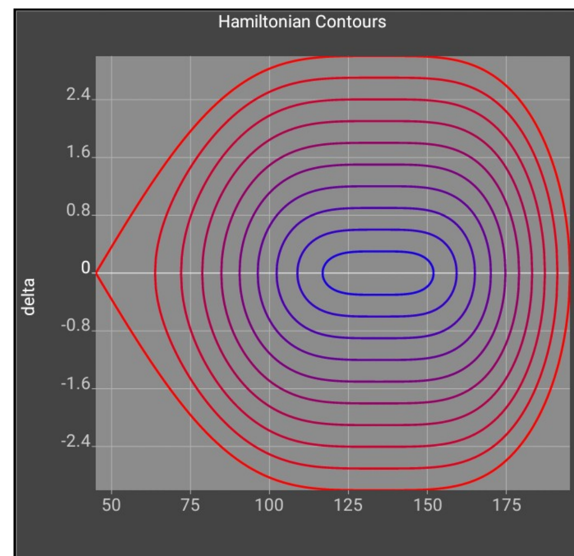




Optimized 4th harmonic HHC increases rms bunch duration from 12.3 ps to 50 ps

Expect a ~4-fold increase in Touschek lifetime and ~4-fold decrease in IBS effects





Computations from TAPAs, version 1.48, tinyurl.com/borlandTAPAs

Modeling methods

- Used parallel **elegant**[1] for tracking
  - Latest versions (27.0+) have significantly improved performance for bunched beams
  - Domain decomposition shares bunches across processors for best performance with multi-particle bunches
- To make tracking faster and concentrate on relevant physics
  - ILMATRIX element for the ring itself
    - Can include chromatic and amplitude detuning (not relevant here)
    - Can include momentum compaction up to third order
  - SREFFECTS for lumped synchrotron radiation
- Turn-by-turn, bunch-by-bunch diagnostics included as needed
  - Phase space coordinates
  - Beam moments
  - Histograms
  - Beam- and generator-induced voltages, phases in cavities
  - Rf feedback system data

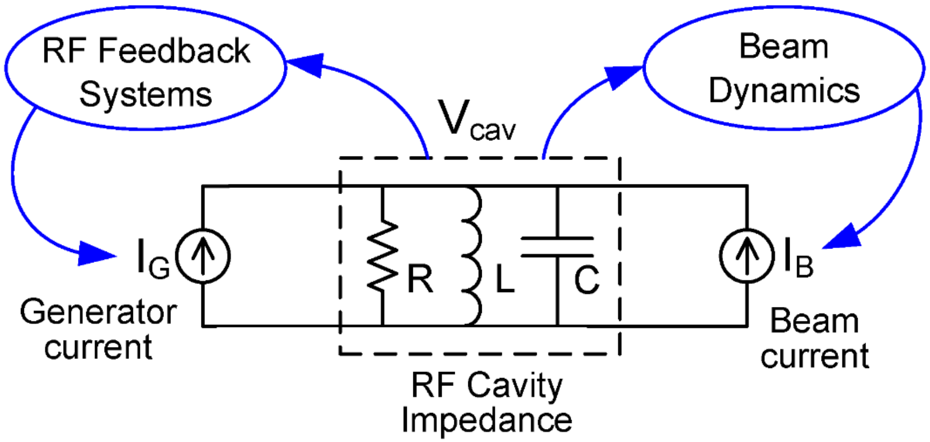
1: M. Borland, LS287, 2000; Y. Wang and M. Borland, AIP Conf. Proc. 877, 214 (2006).

Collective effects and rf modeling

- RFMODE: Beam- and generator-driven rf cavity mode
  - Beam-induced part
    - Uses loss factor plus phasor addition/rotation/damping
    - Implicitly includes the compressive single-turn wake corresponding to the mode
      - Can be turned off if desired
  - Generator-driven part
    - PID feedback seeks to maintain specified net cavity voltage and phase[1]
    - User provides filter coefficients for the controllers
  - Can add other cavity longitudinal and transverse modes if desired (not in present work)
- ZLONGIT[2]: Longitudinal short-range impedance
  - Present instance includes
    - Short range wake from rf cavity HOMs but excluding fundamental
    - Geometric impedance of vacuum chamber computed with GdfidL[3] and ECHO2D
    - Resistive wall impedance computed analytically
- Part of **elegant** since 1994, but recently
  - Improved parallel performance for multi-bunch beams
  - Added rf feedback

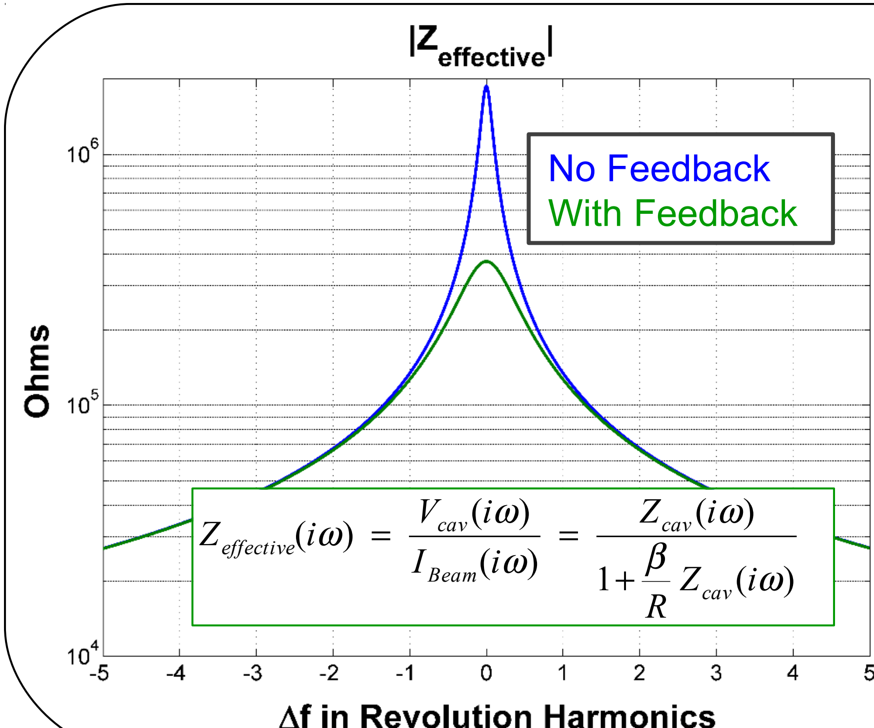
[1]T. Berenc and M. Borland, IPAC15, MOPMA006.
[2]Data from R. Lindberg, A. Blednykh, and Y.-C. Chae.
[3]www.gdfidl.de

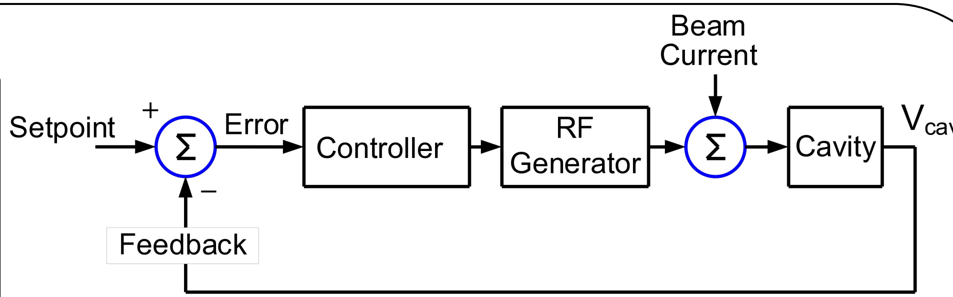
RF Feedback



RF feedback:

- Regulates the RF cavity fields
- Rejects disturbances including beam loading
- Changes the impedance that the beam sees
- Note: in Bunch Lengthening System, main RF contributes to Robinson damping while the harmonic RF cavity contributes to growth





Example: Direct RF Feedback

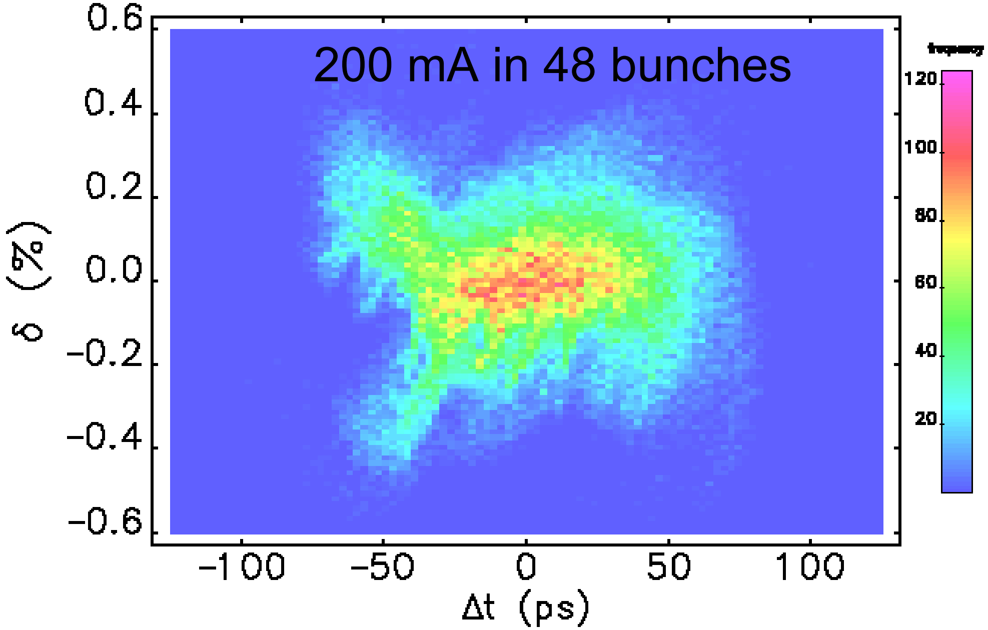
§ Simple Proportional Gain

=> Controller = $\frac{\beta}{R}$, β = Loop Gain at resonance

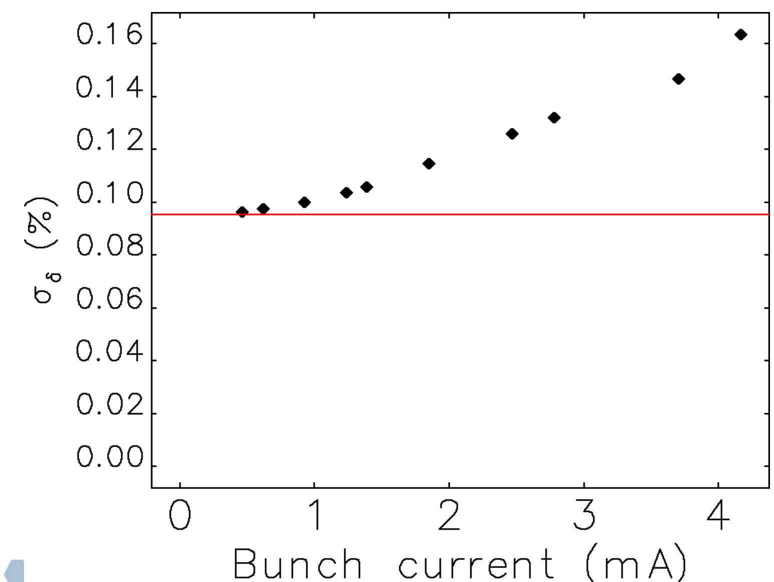
§ R and Q are reduced by (1 + Loop Gain)

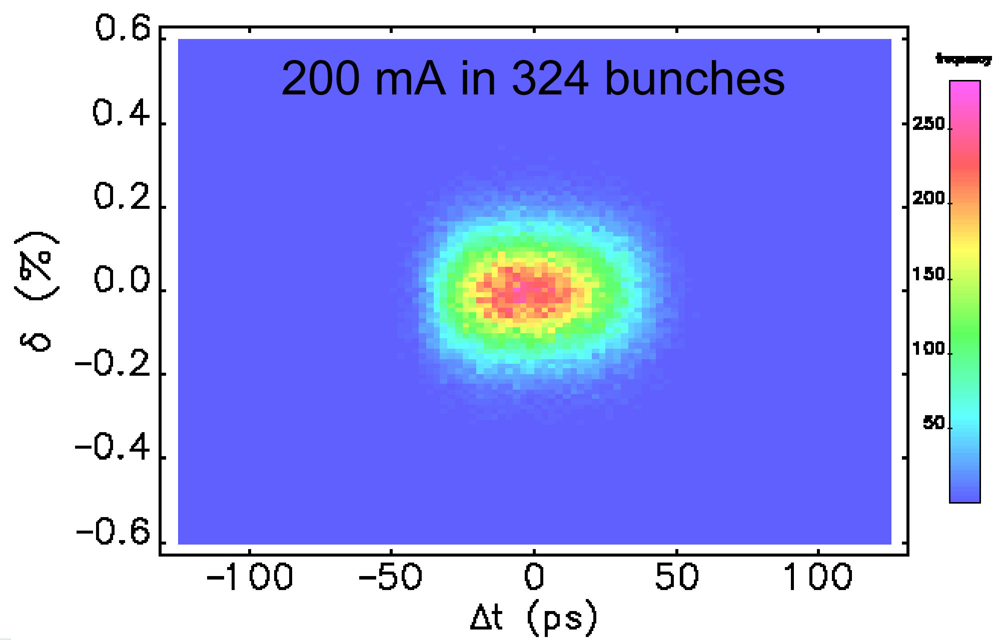
§ R/Q stays the same

Longitudinal phase space without HHC

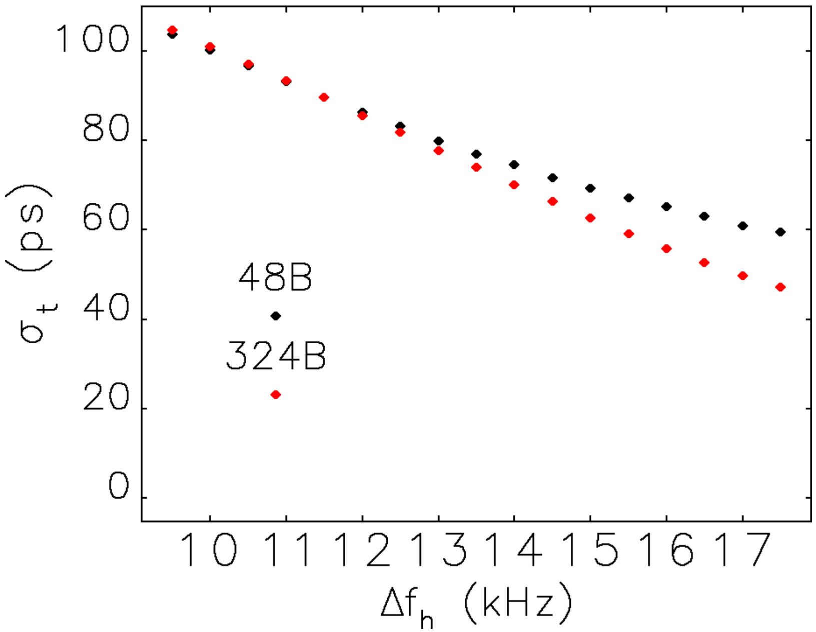


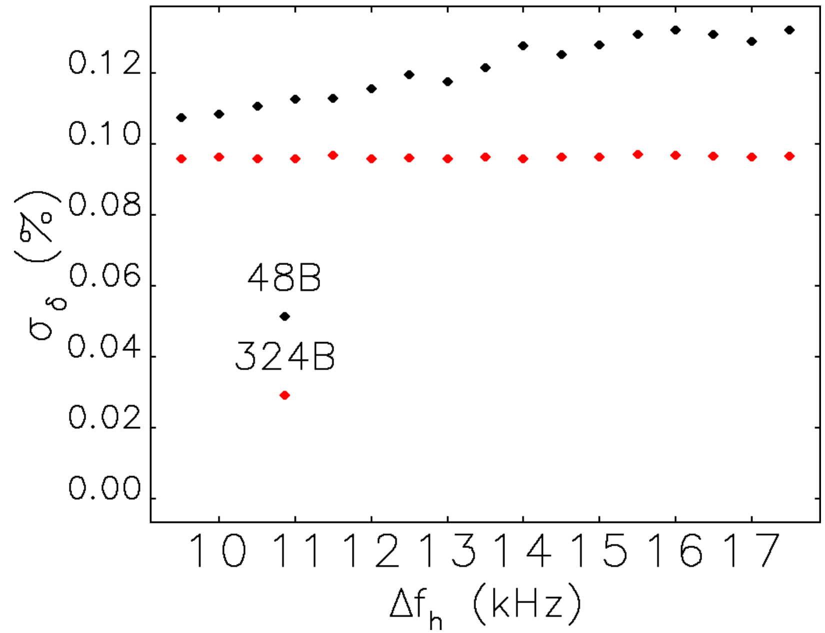
- Results similar with 10^4-10^6 simulation particles/bunch
- Microwave instability threshold is at ~0.5 mA/bunch
  - In APS, threshold is ~7 mA/bunch





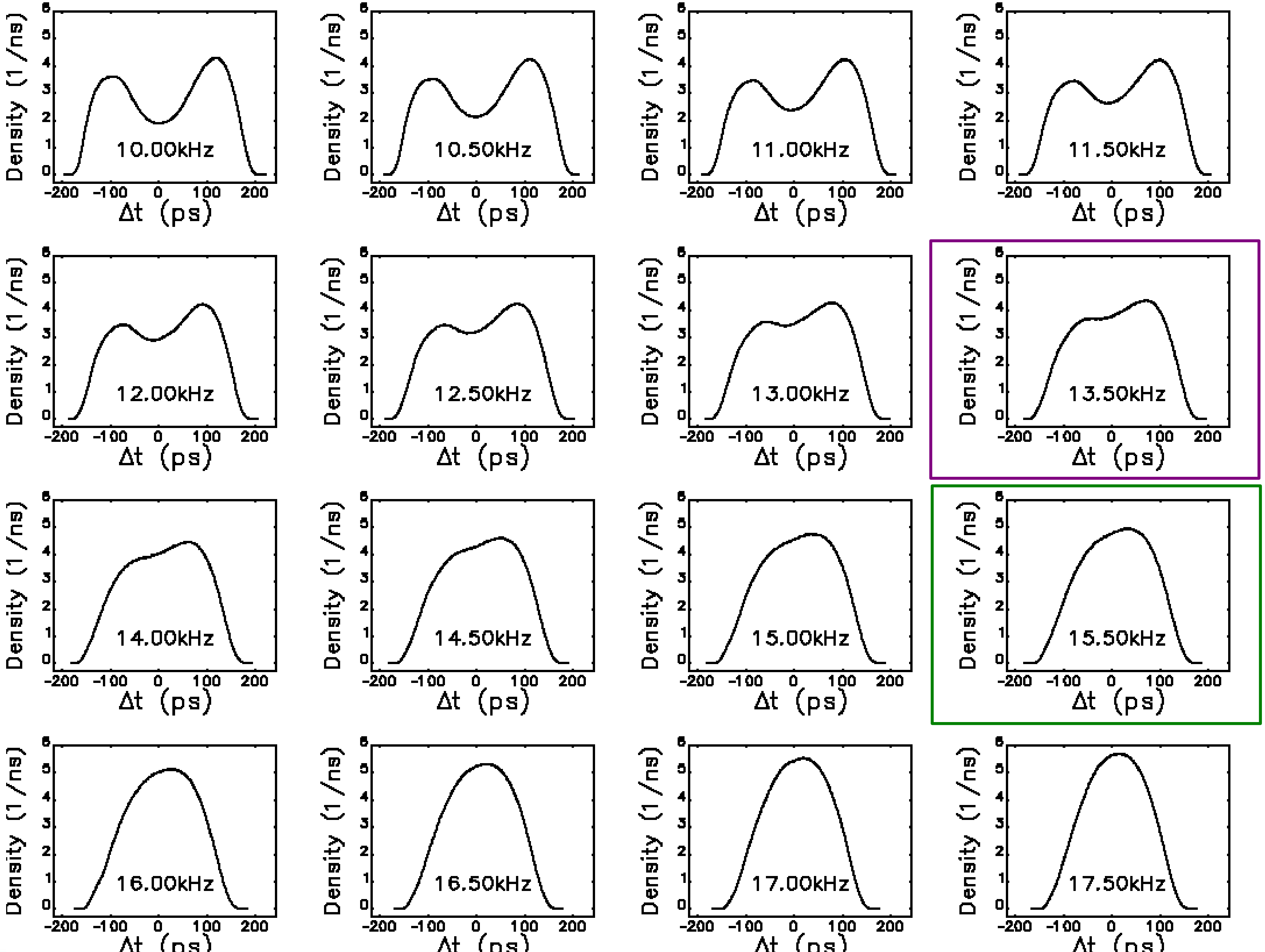
Scan of HHC detuning



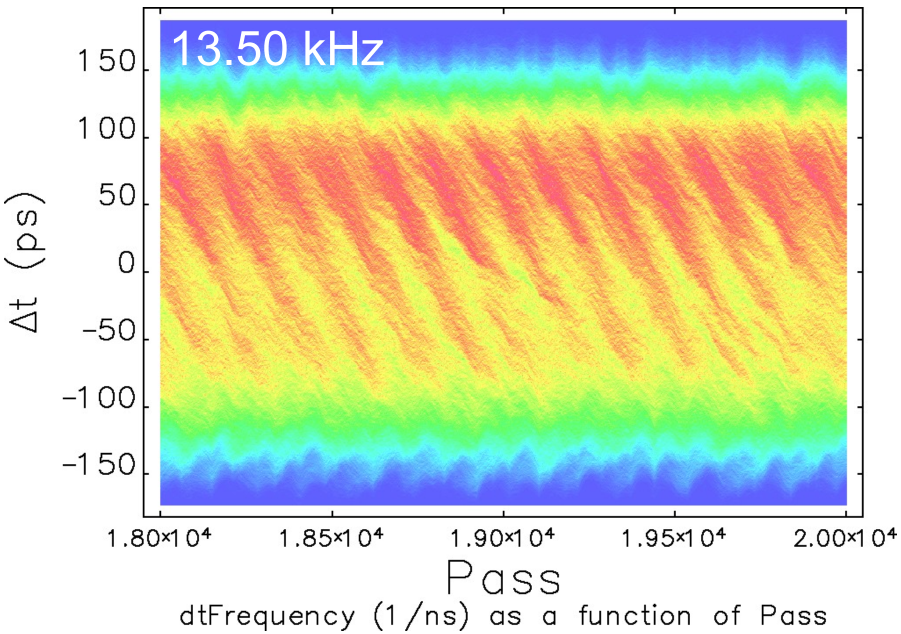


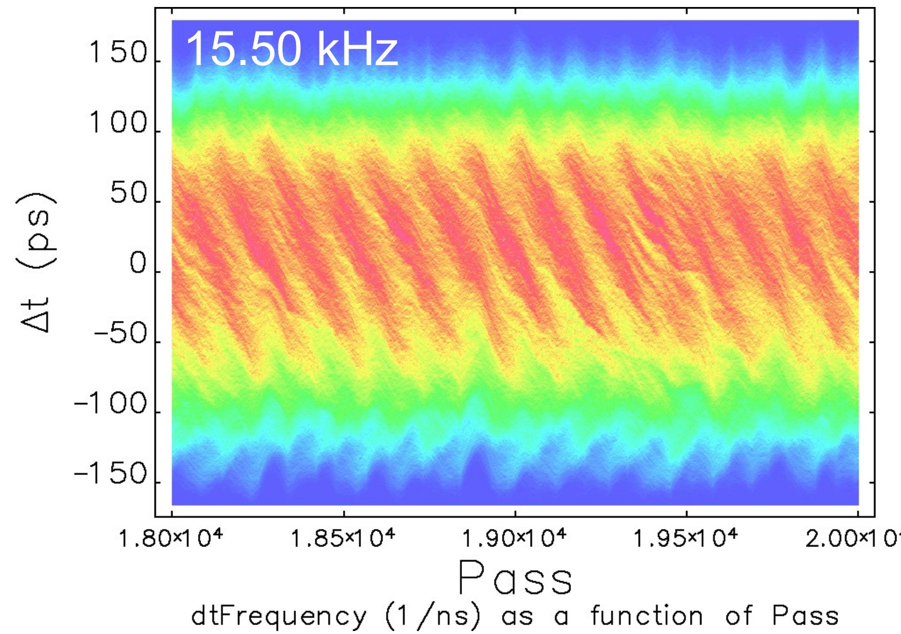
- As expected, bunch lengthens as HHC cavity is tuned toward resonance
- “Beneficial” effect of MWI visible for 48-bunch mode
- As bunch lengthens with decreased detuning, MWI is suppressed and energy spread drops
- Expected optimum bunch length from theory (without impedance) is 50 ps with ~16.5 kHz detuning
  - 324-bunch results agree with this expectation
  - Seems we can go beyond that...

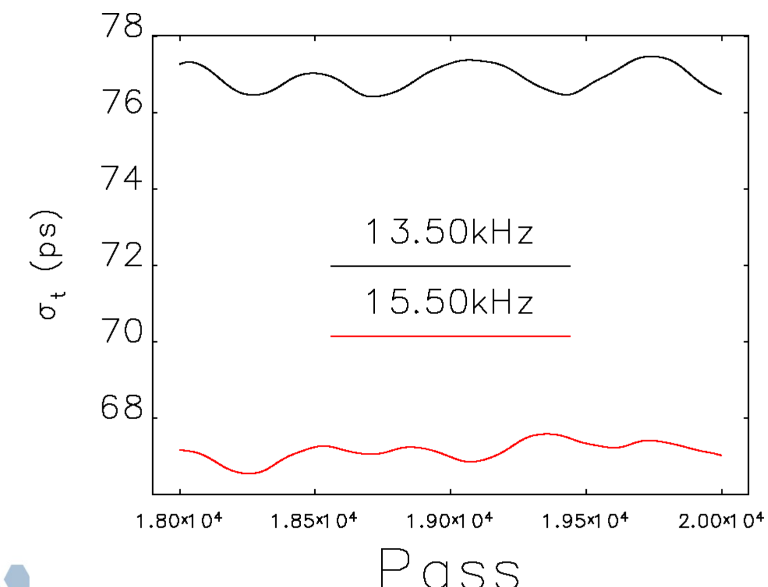
Longitudinal density averaged over 2000 turns (48B)



Longitudinal density is noisy, but rms is stable (48B)







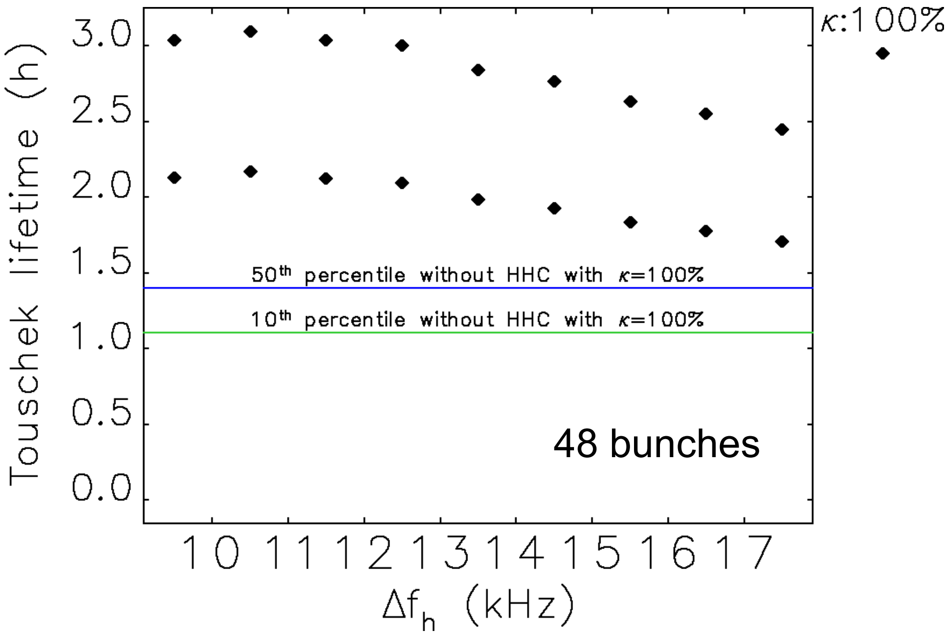
- Results on previous slide average out the effect of MWI
- Turn-by-turn variation seems mostly MWI-driven
  - Present with cavity detuned by +136kHz (f_{rev}/2) as well
- Not related to rf feedback
- How much do users care about this?

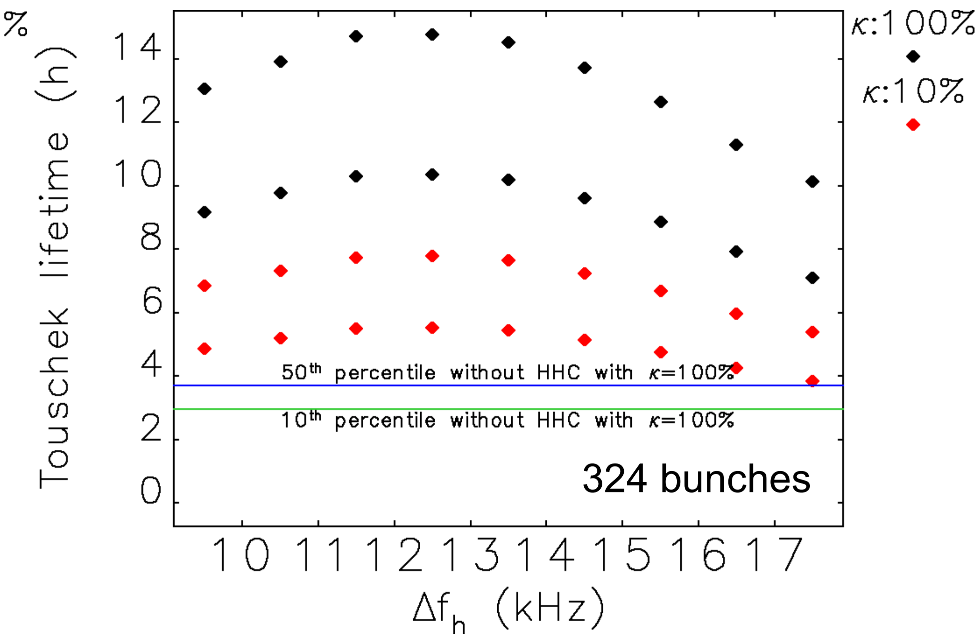
Touschek lifetime analysis

- Touschek lifetime is one reason for introducing HHC
- Normally, to compute it, just use rms bunch duration
- Using tracking results improves fidelity of calculations
  - Tracking results give bunch distribution turn-by-turn
  - Slice analysis of bunch on each pass gives current density and slice energy spread
    - Slice energy spread includes MWI
  - Program **touschekLifetime** allows slice-based Touschek lifetime calculation[1]
- Also included IBS effect on emittance and energy spread
  - Computations used **ibsEmittance**[2]
- In addition, need local momentum acceptance[3]
  - Used 100 error ensembles with lattice correction[4] as input to tracking
- Computations provide a Touschek lifetime value for each error ensemble, averaged over many bunch samples
- Method not fully self-consistent, but allows combining effects of intrabeam scattering, HHC, and microwave instability

1: A. Xiao and M. Borland, PRSTAB **13** 074201 (2010); A. Xiao and M. Borland, IPAC15, MOPMA012.
2: A. Xiao *et al.*; M. Borland *et al.*, PAC03, 3461.
3: C. Steier et al., Phys. Rev. E 65-056507 (2002); M. Belgroune et al., PAC 2003, 896.
4: V. Sajaev, IPAC15, MOPMA010.

Touschek Lifetime Improvements due to HHC[1]



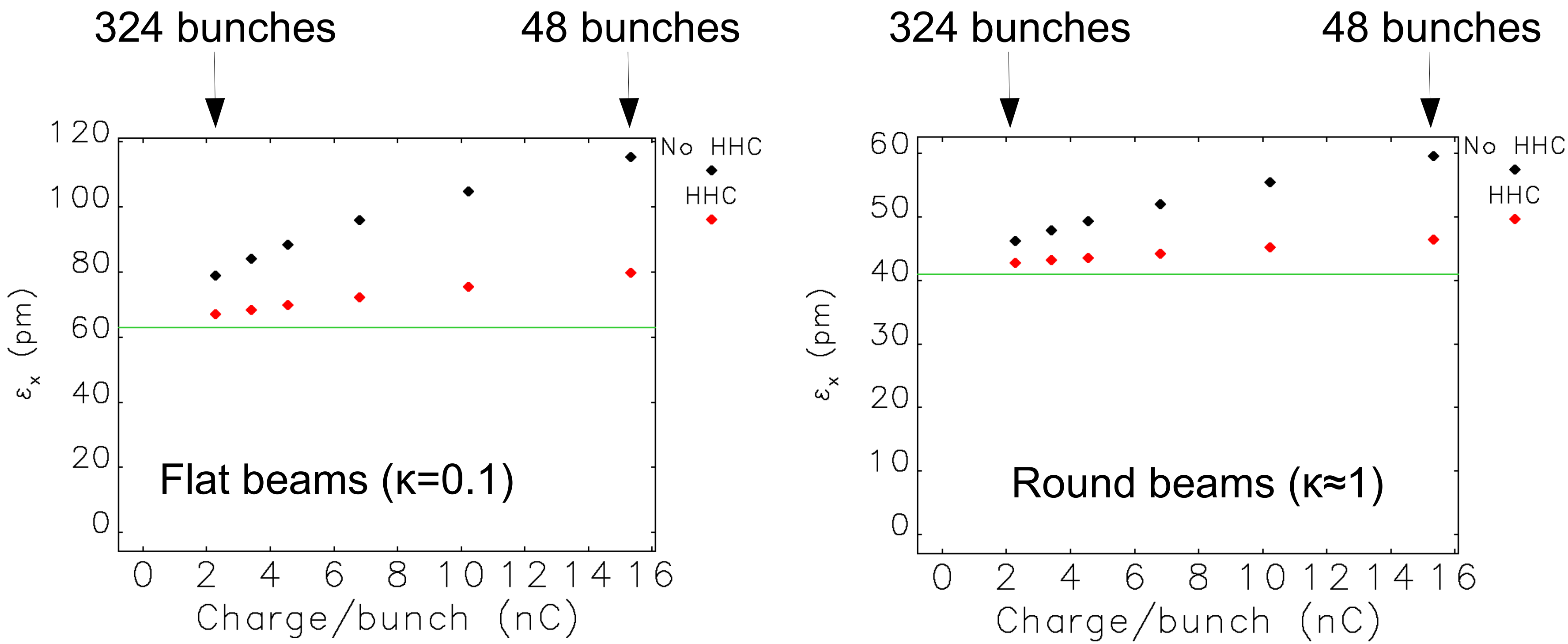


- In both cases, have 200 mA, Q_L=600k
- For 48 bunches, get factor of ~2 for 13.5 kHz detuning
  - Bunch is already significantly lengthened by the ring impedance
  - Do not reach the desired 7.5 h value
  - Has implications for shielding, TBD
- For 324 bunches, get factor of ~3 for 13.5 kHz detuning
  - Total lifetime (including gas scattering) expected to meet goal for round beams
  - Flat beams (2x higher brightness) more challenging

Symbols show 10th (lower) and 50th (upper) percentile points in lifetime distributions

1: A. Xiao and M. Borland, IPAC15, MOPMA012.

Suppression of IBS



- Approximate results with gaussian beams show the beneficial effect of HHC
  - Uses program **ibsEmittance**[1]
- Improvement is dramatic for flat beams and high charge
- Not negligible even for 324 bunch flat beams

1: A. Xiao *et al.*; M. Borland *et al.*, PAC03, 3461.

Tracking-based HHC Simulation with IBS

- Previous results are only approximate, using gaussian longitudinal distribution
- Would like to perform <u>self-consistent</u> modeling of five effects
  - Intrabeam scattering
  - Longitudinal impedance
  - Higher harmonic cavity
  - Main rf cavity with feedback
  - Element-by-element synchrotron radiation
- This will give vertical and horizontal emittance consistent with complex longitudinal distribution that results from IBS, cavities, and impedance
- Effect of IBS and MWI on the energy spread and bunch shape simultaneously included

Problems

- Impedance modeling requires >30k particles/bunch
- Must use slice-based IBS algorithm[1] to be accurate
  - ~20 slices needed to reproduce a non-gaussian bunch shape
  - Need ~100 k particles/bunch to ensure reasonable slice populations
- Cavity/feedback modeling nominally requires all N bunches
  - Different bunch patterns give different V(t) envelopes for cavities
- With so many particles element-by-element tracking is very time-intensive
- Simulations would take *many months* to run

1: A. Xiao and M. Borland, IPAC15, MOPMA012.

Solution[1]

- Track only one of N bunches
  - HHC and main cavity must be fooled into thinking N bunches are present
  - Other effects are all accurately represented with a single bunch
  - Speed-up: ~48x for N=48
- Perform complex IBS integrals in parallel
  - Integrals over lattice functions *for each beam slice*
  - Parallelized the evaluation of these integrals
  - Speed-up: ~10x for 500 cores

MOP093 Proceedings of LINAC08, Victoria, BC, Canada

STUDY OF IBS EFFECTS FOR HIGH-BRIGHTNESS LINAC BEAMS *

A. Xiao†, ANL, Argonne, IL 60439, USA

Abstract

Intrabeam scattering (IBS) may become an issue for linac-based fourth-generation light sources such as X-ray free-electron lasers and energy recovery linacs (ERLs), both of which use high-brightness electron beams with extremely small emittance and energy spread. Any degradation of this extremely high beam quality could significantly reduce the machine's performance. We present here a strategy first used in the code `elegant` [1] for simulating IBS effects for high-brightness linac beams. We also present an application to a possible ERL upgrade of the Advanced Photon Source.

INTRODUCTION

Particles in a beam exchange energy between transverse and longitudinal oscillations due to Coulomb scattering. Depending on the scattering angles, the process leads to a diffusion in beam size (intrabeam scattering or IBS) or beam loss (Touschek effect).

The theory of IBS is discussed in several publications [2, 3]. A number of codes (e.g., ZAP [4], MAD-X [5]) have been developed for calculating the beam size growth rates. In the past, particle densities were not very high, so the growth times were much longer than the time spent traversing a typical linac. Thus, codes were designed for the stored beam case only with a constant beam energy. Linac-based fourth-generation light sources, such as X-ray free-electron lasers and Energy Recovery Linacs (ERLs [6]), require a high-brightness electron beam with extremely small emittance and energy spread. Any degradation of the beam quality could significantly reduce the machine's performance. Since the IBS growth time becomes much shorter for a high-brightness beam, IBS effects may become an issue even for a linac beam.

To investigate this issue, we modified the IBS calculation in `elegant` to include vertical dispersion effects and added the ability to handle acceleration. We applied our code to a proposed APS-ERL [7, 8] upgrade lattice also. Our results show that the IBS effects is moderate with the designed beam parameters.

CALCULATION OF IBS GROWTH RATES

A detailed formalism for intrabeam scattering, taking into account the variation of lattice functions with azimuth, has been developed by Bjorken and Mtingwa [3]. The expression of emittance growth rate τ_d in the direction d (x, y, or z) is given by (3.4) in [3] as:

$$\frac{1}{\tau_d} = \frac{\pi^2 c r_0^2 m^3 N ln\Lambda}{\gamma\Gamma} f,$$

$$f = \left\langle \int_0^\infty \frac{\lambda^{1/2} d\lambda}{\sqrt{|A|}} \left\{ Tr L^d Tr[A^{-1}] - 3Tr[L^d (A)^{-1}] \right\} \right\rangle, \quad (1)$$

where c is the speed of light, r_0 is the classical particle radius, m is the particle mass, N is the number of particles per bunch (or in the beam for unbunched case), $ln\Lambda$ is a Coulomb logarithm, γ is the Lorentz factor, Γ is the 6-dimensional invariant phase-space volume of the beam,

$$\Gamma_B = (2\pi)^3(\beta\gamma)^3 m^3 \varepsilon_x \varepsilon_y \sigma_p \sigma_z \qquad (bunched)$$
$$\Gamma_U = 4\pi^{5/2}(\beta\gamma)^3 m^3 \varepsilon_x \varepsilon_y \sigma_p (2\pi R) \quad (unbunched), \quad (2)$$

and $A = (L + \lambda I)$, with

$$\begin{aligned} L &= L^x + L^y + L^z, \\ L^x &= \frac{\beta_x}{\varepsilon_x} \begin{pmatrix} 1 & -\gamma\phi_x & 0 \\ -\gamma\phi_x & \gamma^2(\frac{D_x^2}{\beta_x^2} + \phi_x^2) & 0 \\ 0 & 0 & 0 \end{pmatrix}, \\ L^y &= \frac{\beta_y}{\varepsilon_y} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \gamma^2(\frac{D_y^2}{\beta_y^2} + \phi_y^2) & -\gamma\phi_y \\ 0 & -\gamma\phi_y & 1 \end{pmatrix}, \quad (3) \\ L^z &= \frac{\gamma^2}{\sigma_p^2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}. \end{aligned}$$

Here, $\phi_{x,y} = D'_{x,y} + \frac{\alpha_{x,y} D_{x,y}}{\beta_{x,y}}$; $\varepsilon_{x,y}$ and $\sigma_{p,z}$ are beam distribution related quantities; and $\beta_{x,y}, \alpha_{x,y}, D_{x,y}, D'_{x,y}$ are local optical functions.

Equation (3), which includes vertical dispersion effects, is used in `elegant` for calculating the beam size growth rate. We found there are missing terms in MAD-X in the expressions for $a_{x,y}$ and $b_{x,y}$ used in formula (8) in [9], as confirmed by the developer [10]. The following equations show the differences between a_x in `elegant`,

$$\begin{aligned} a_x &= 2\gamma^2\left(\frac{H_x}{\varepsilon_x} + \frac{H_y}{\varepsilon_y} + \frac{1}{\sigma_p^2}\right) - \frac{2\beta_x}{\varepsilon_x} - \frac{\beta_y}{\varepsilon_y} \\ &\quad - \frac{\beta_x H_y}{H_x \varepsilon_y} + \frac{\beta_x}{H_x \gamma^2}\left(\frac{2\beta_x}{\varepsilon_x} - \frac{\beta_y}{\varepsilon_y} - \frac{\gamma^2}{\sigma_p^2} + \frac{6\beta_x}{\varepsilon_x}\gamma^2\phi_x^2\right) \end{aligned} \quad (4)$$

* Work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.
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Extreme Beams and Other Technologies 4D - Beam Dynamics, Computer Simulation, Beam Transport

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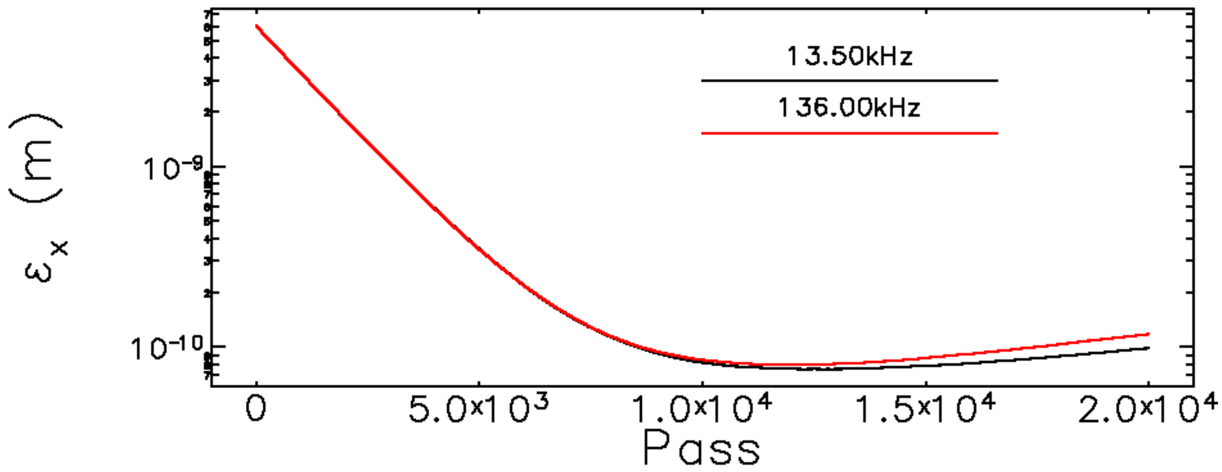
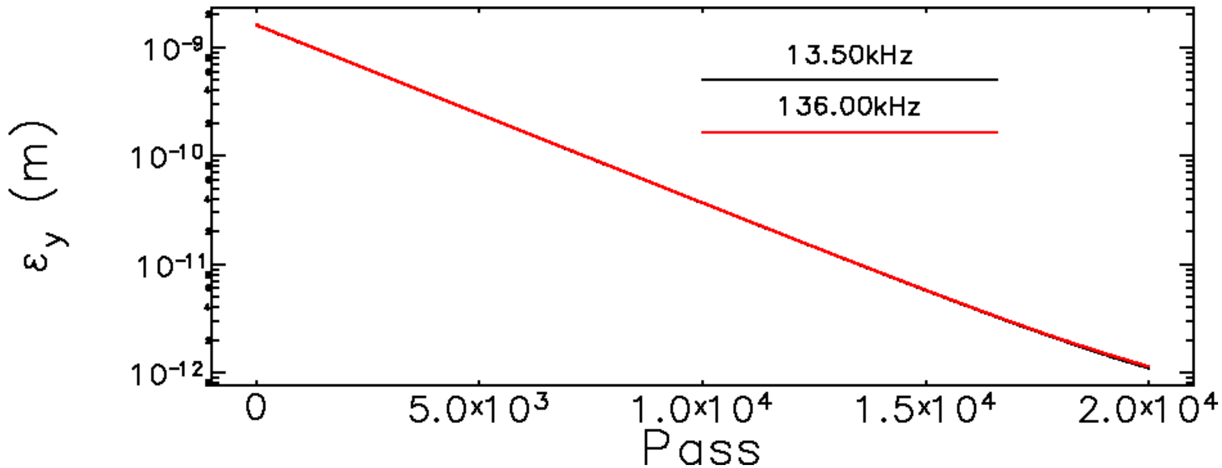
1: M. Borland *et al.*, IPAC15, MOPMA009.

Tracking Simulation with IBS, HHC, Impedance, …





- Performed test runs simulating damping of a injected bunch
- Coupling is very low
- As vertical emittance damps to very small value, horizontal emittance increases due to IBS
- Effect is stronger with HHC detuned to 136 kHz
- Production runs pending availability of computer time
  - Need about 60 hours on 480 cores for one run

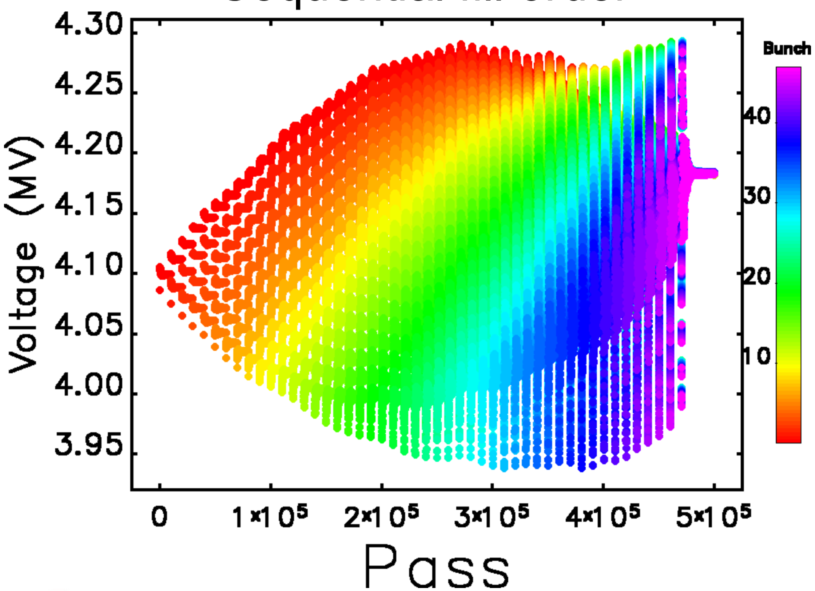
Operational Issues

- So far, we've looked at the performance of the HHC in ideal conditions
  - Uniformly-spaced fills
  - Uniform bunch population
- Operational issues complicate matters
  - Filling from zero produces transient irregular fill patterns
  - Not all bunches will be filled with exactly the same current
  - Bunches may be accidentally kicked out
  - Energy loss per turn varies in time as gaps are changed
- All of these effects have been simulated

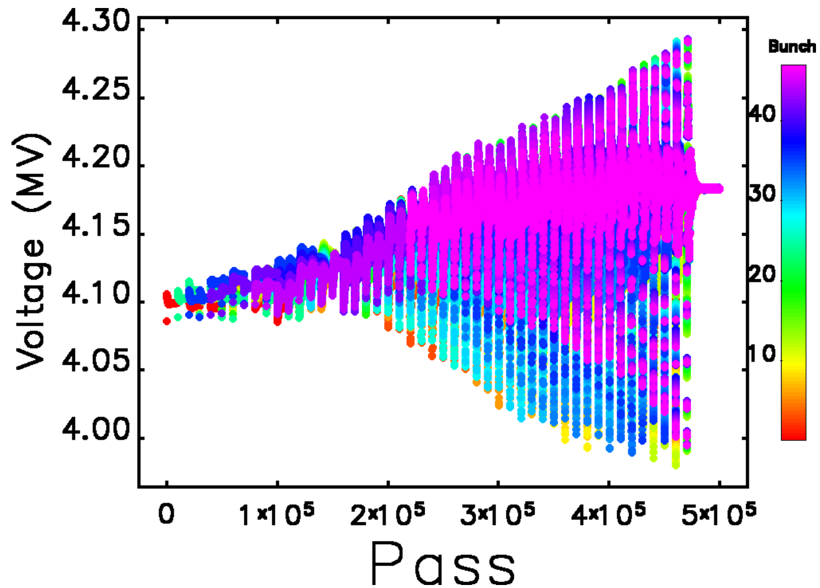
Simulations of 48-Bunch Filling from Zero

- Wanted to assess potential for beam loss due to voltage, phase variation
  - Sequential fill: 0, 27, 54, …, 1269
  - Balanced fill: 0, 648, 324, 972, …
- Simulations allow 37 ms (10,000 turns) between injections, sufficient for damping and feedback to settle
- Although transient voltage levels are similar, balanced fill shows smoother voltage across bunches

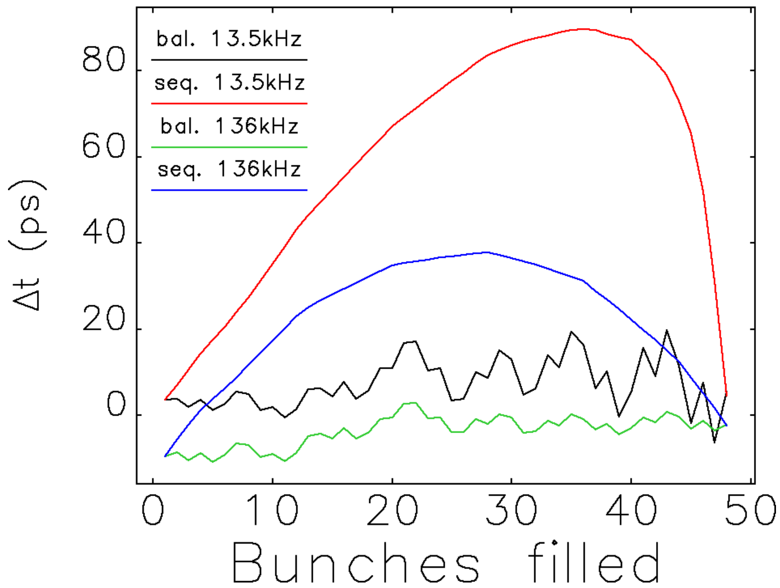
Sequential fill order



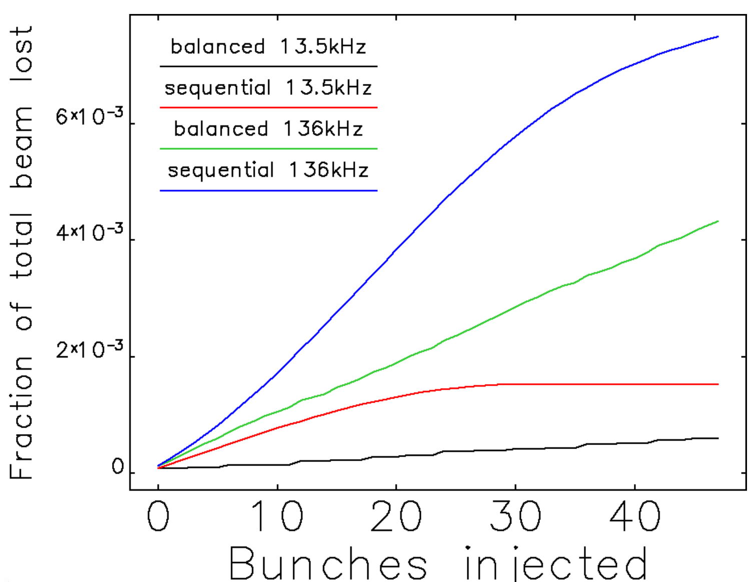
Balanced fill order



Simulations of 48-Bunch Filling from Zero



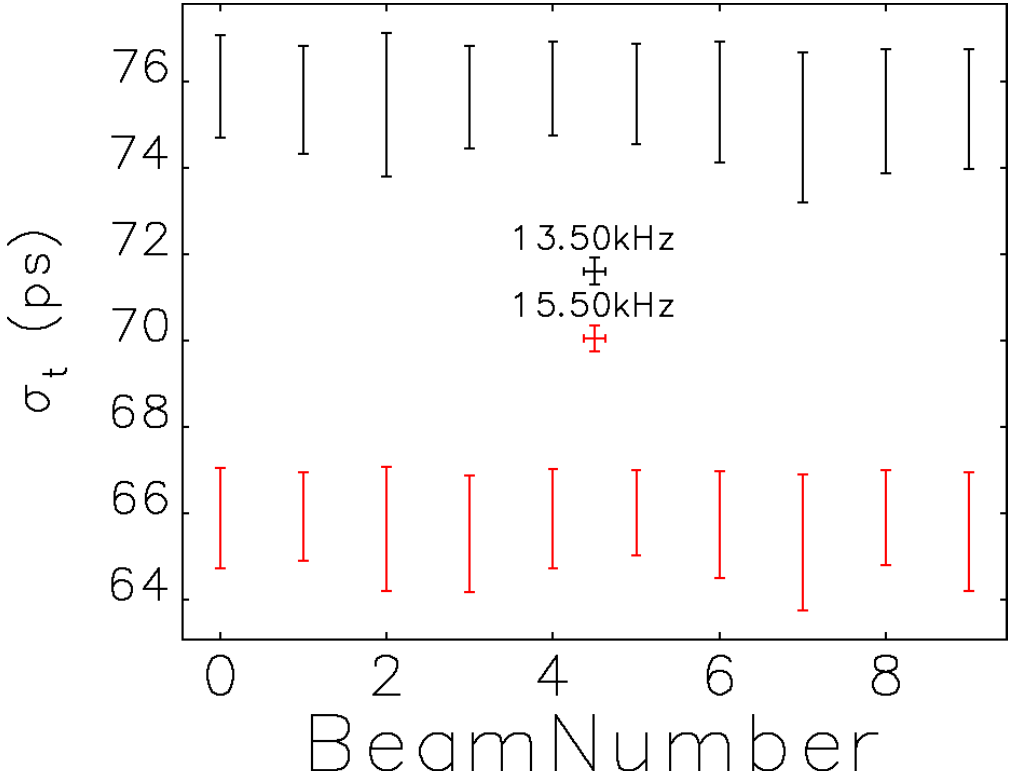
- Timing shifts are much larger for the sequential fill order
- Timing shifts are smaller when HHC is detuned to 136 kHz



- Losses are low in all cases
- Losses are larger for sequential fill order
- Tuning HHC to 13.5 kHz improves capture efficiency
  - Seems intuitive since bucket is bigger

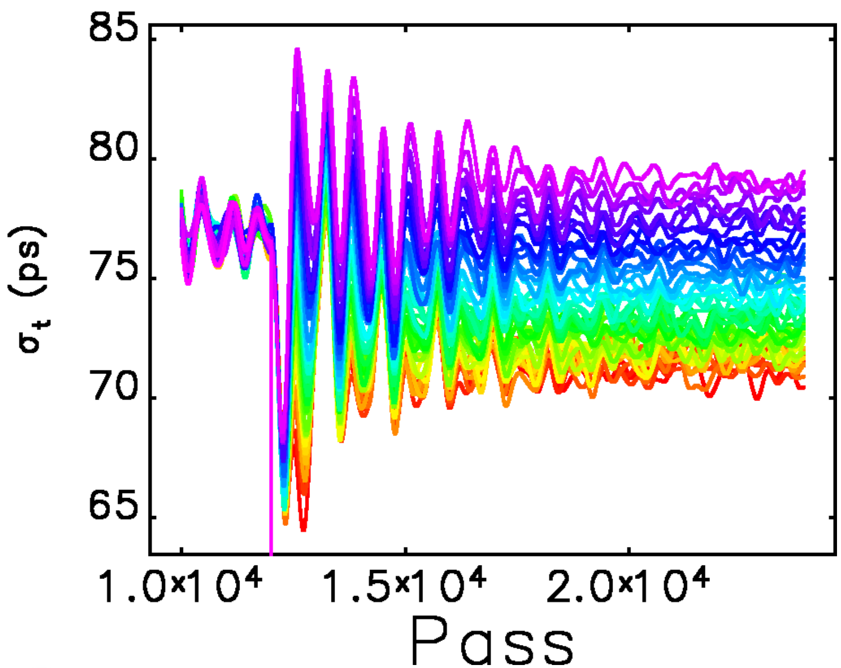
Effect of bunch population variation

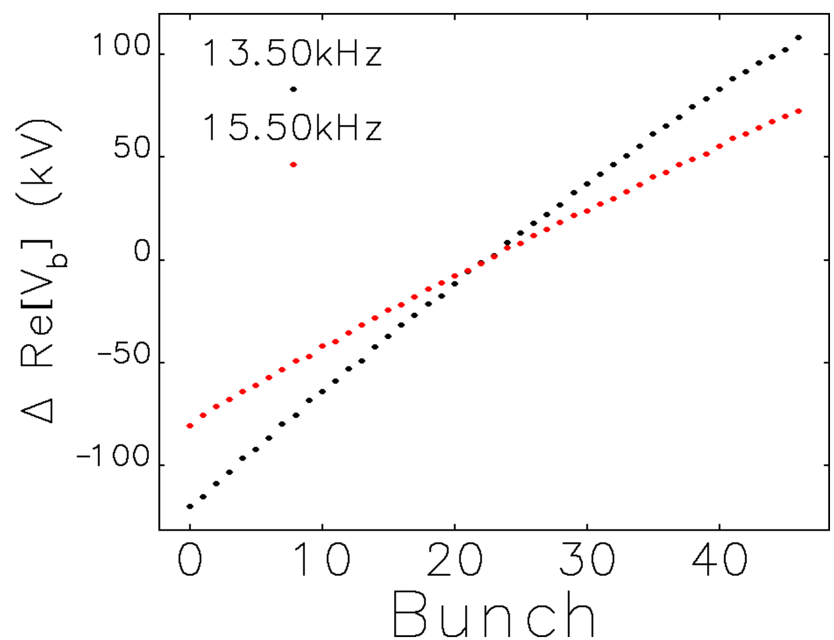
- Bunches will be swapped out when they fall to 90% of initial charge
- Expect to have randomly-ordered bunches with uniform distribution of charge between 105% and 95% of the average value
- Simulated 10 random 48-bunch fills of this type
- Modest variation among bunches within a fill and over time



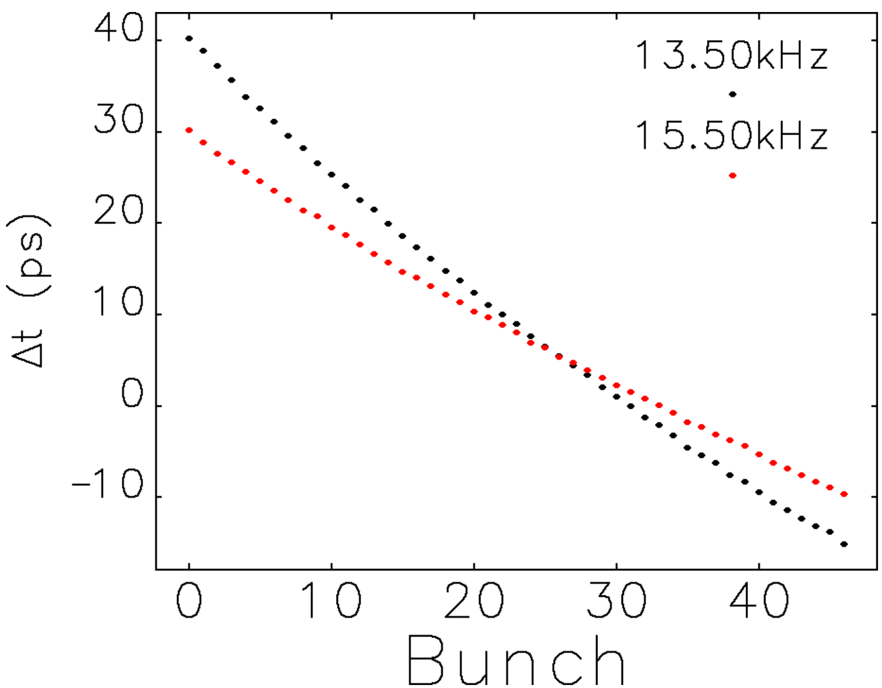
Effect of lost bunch (48 bunches, minus 1)

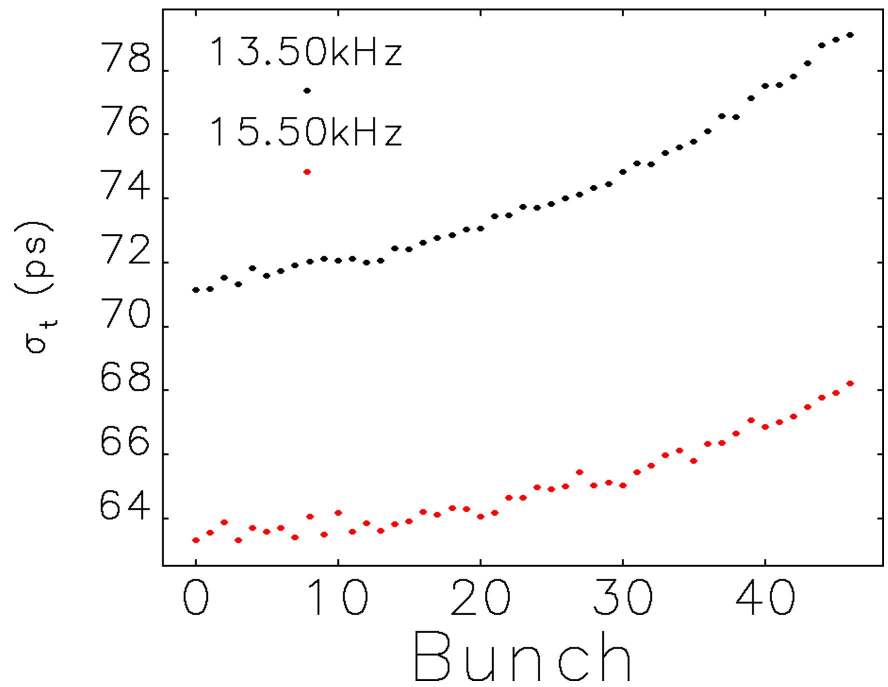
- Swap-out involves kicking out one bunch and immediately injecting replacement
  - May fail sometimes to inject the replacement
- Simulated kicking out of last bunch in 48-bunch fill, then return to equilibrium
  - No particle loss observed even with ±2% momentum acceptance
- Real part of beam-induced field in main cavity has ~160-230 kV sawtooth
  - Forces bunches to shift phase
  - Changes effect of HHC





Effect of lost bunch (48 bunches, minus 1)

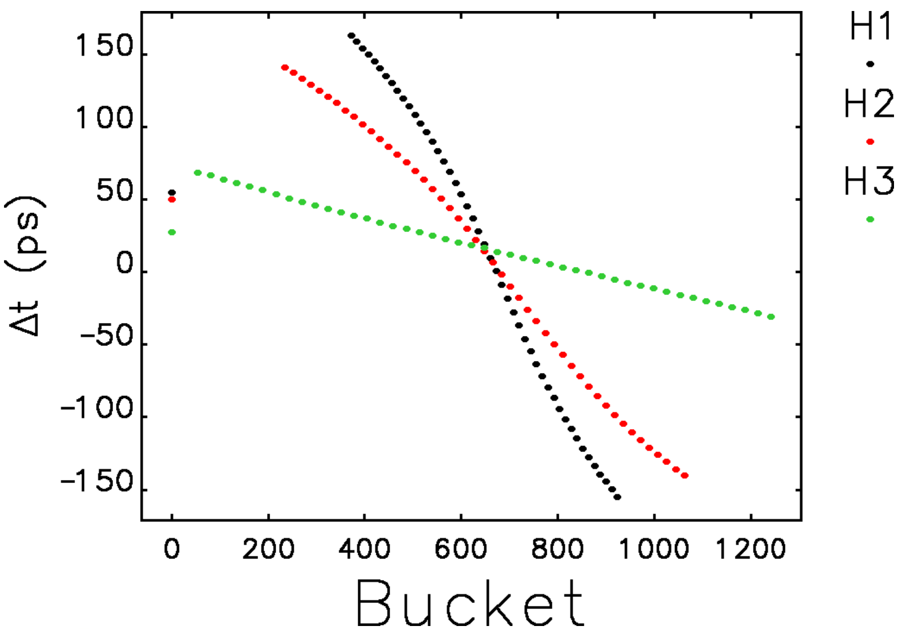


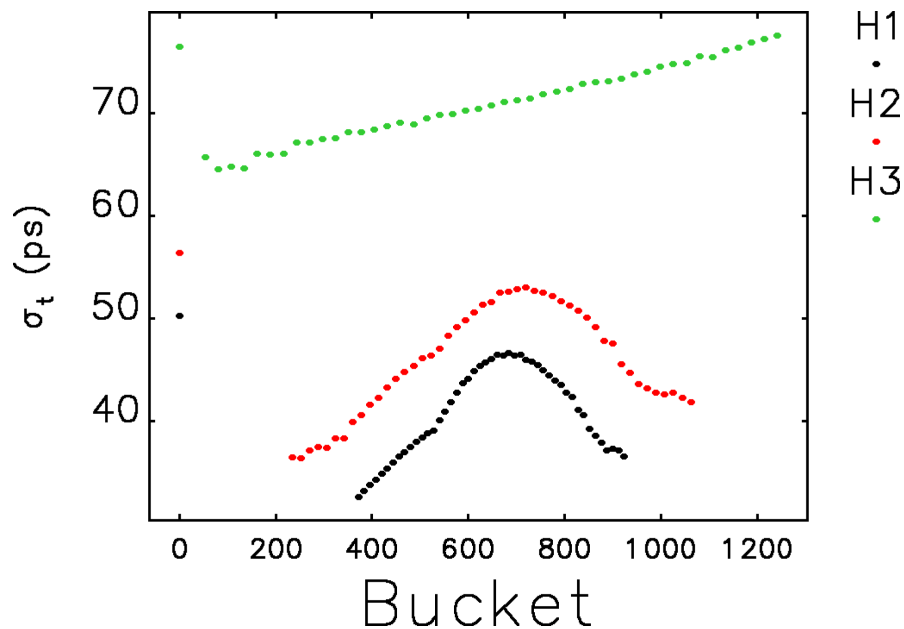


- Variation in the bunch centroid is a significant fraction of the bunch length
  - Is this a problem for users?
- Bunch length variation is under 10%, presumably tolerable
- Could provide gate to users to indicate when a bunch is missing
- ~7 degree phase shift at main rf system frequency
  - May want to adjust injector phase to hit the optimum point in the bucket

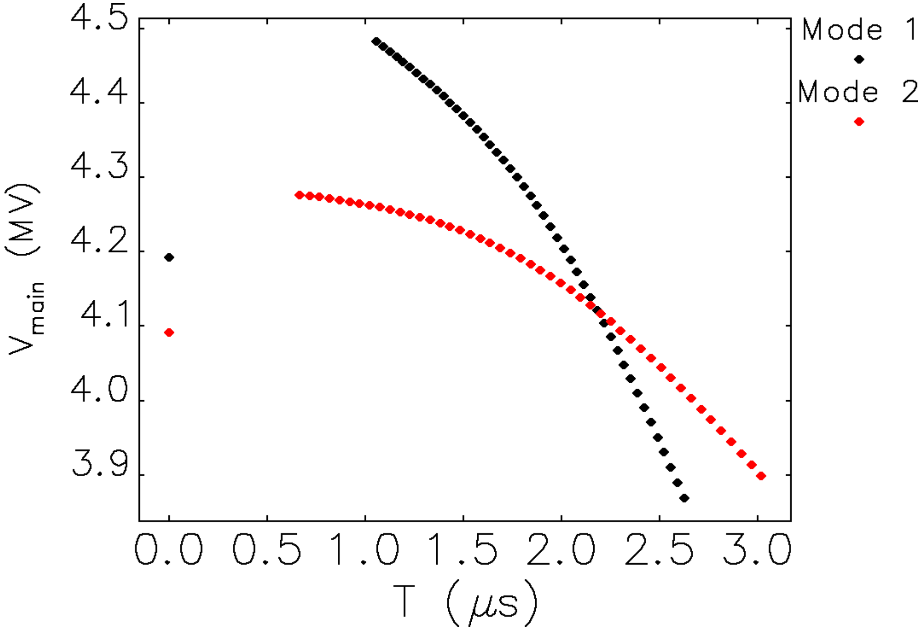
Hybrid Modes

- Looked at three possible hybrid modes with equal bunches
  - H1: 47 bunches at 12 bucket spacing with ±1.05 μs gap around single bunch
  - H2: 47 bunches at 18 bucket spacing with ±0.66 μs gap around single bunch
  - H3: 45 bunches at 27 bucket spacing with ±0.15 μs gap around single bunch
- As expected, significant non-uniformity in bunch properties
  - H1, H2 do not approach ~75 ps bunch duration seen in uniform 48-bunch mode
  - Difficult lifetime situation made significantly worse
  - Arrival time variation also large for H1, H2

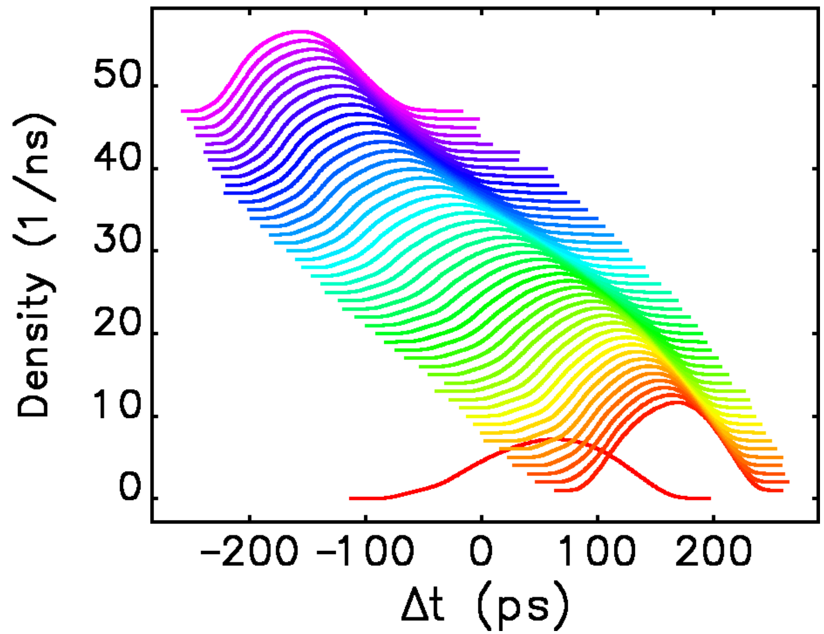




Hybrid mode



Mode 1, 13.5kHz densities averaged over 2000 turns



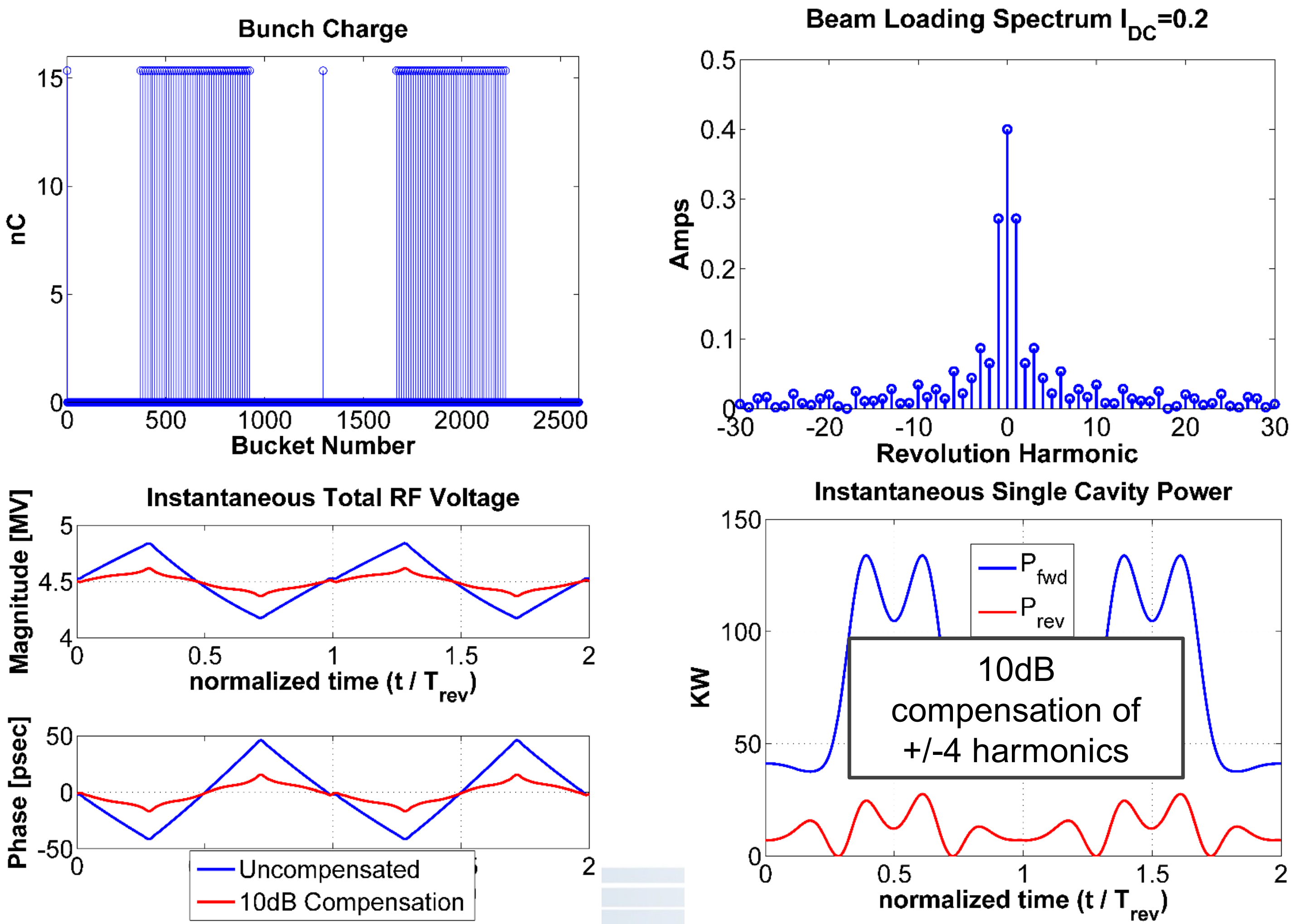
- Main cavity voltage shows a significant modulation
- Present rf feedback system is not fast enough to counteract this
  - Response time is about 20 ms
- Studying a faster system that should better compensate
  - H1 and H2 will be very challenging
- Should be significantly easier to improve H3 mode

RF Feedback: Other Types of Feedback

- Polar (Amplitude / Phase) or Cartesian (in-phase / quadrature): can be narrowband or wideband
- Comb Filters: reduce impedance & beam-loading at revolution harmonics & synchrotron sidebands
- Feed-Forward: feed wall-current monitor to generator to cancel the beam-current directly

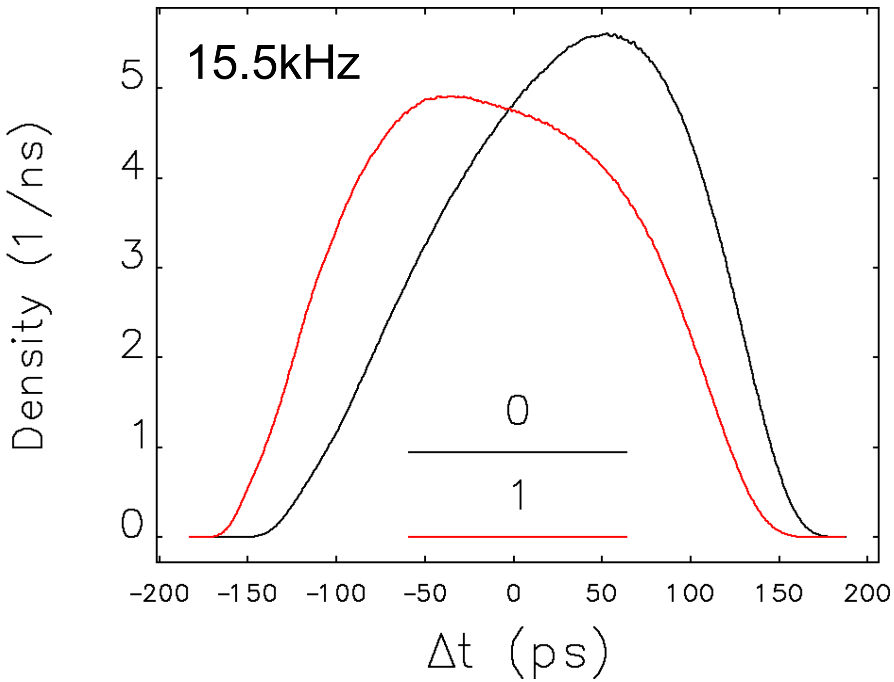
Example of Transient Beam-Loading Compensation for Hybrid Fill

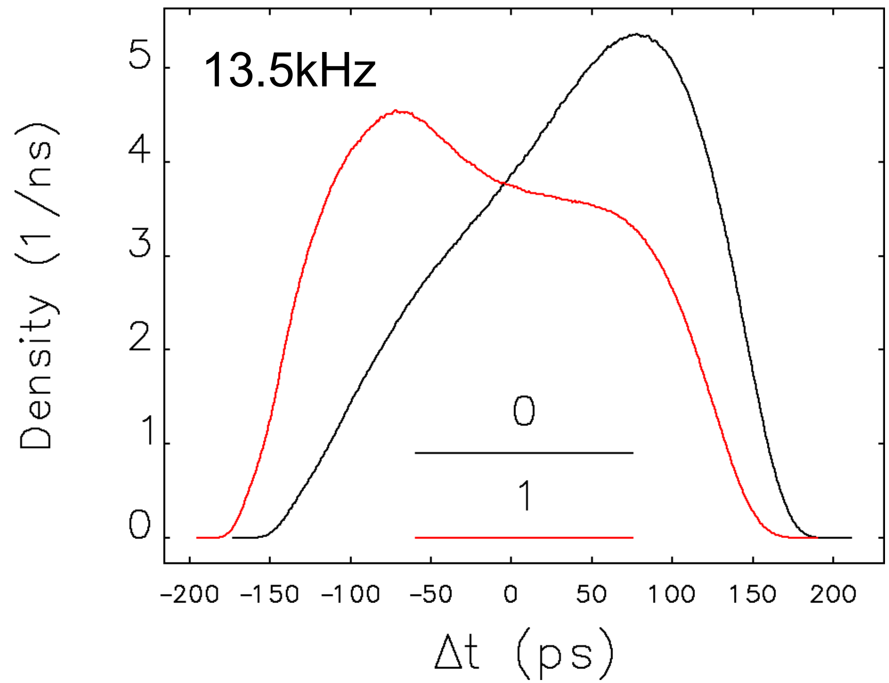
(can be achieved with combination of above)



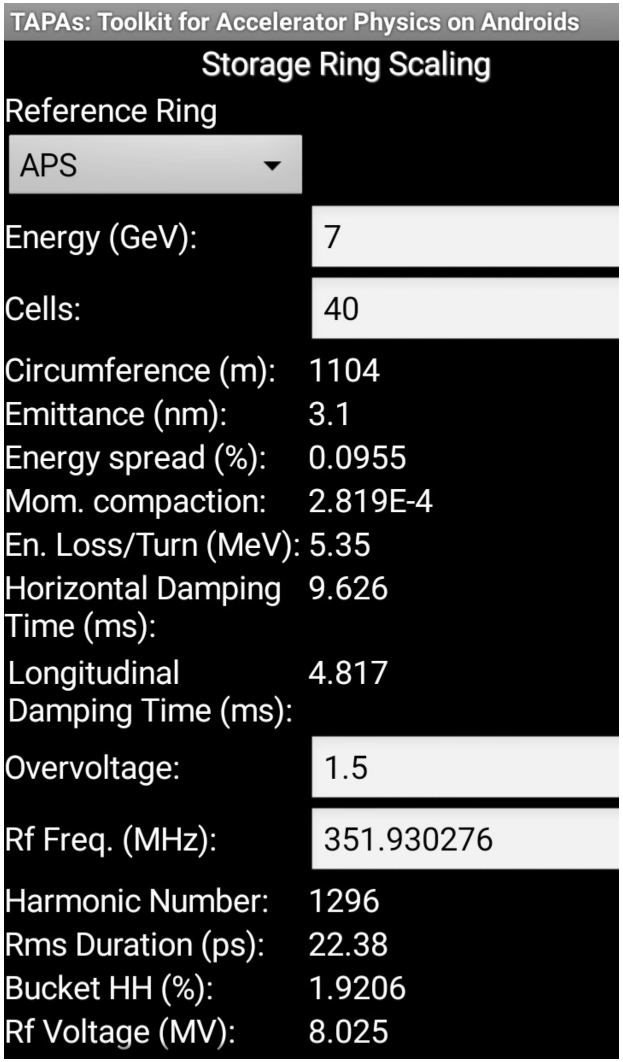
Another possibility: 24 doublets

- Could fill 24 pairs of buckets with uniform separation between pairs
  - Pair forms a "super-bunch" 11.4 ns in duration
  - 142 ns gap between pairs
- This actually works pretty well
  - 13.5kHz: 70-76 ps rms bunch duration
  - 15.5kHz: 63-67 ps rms bunch duration



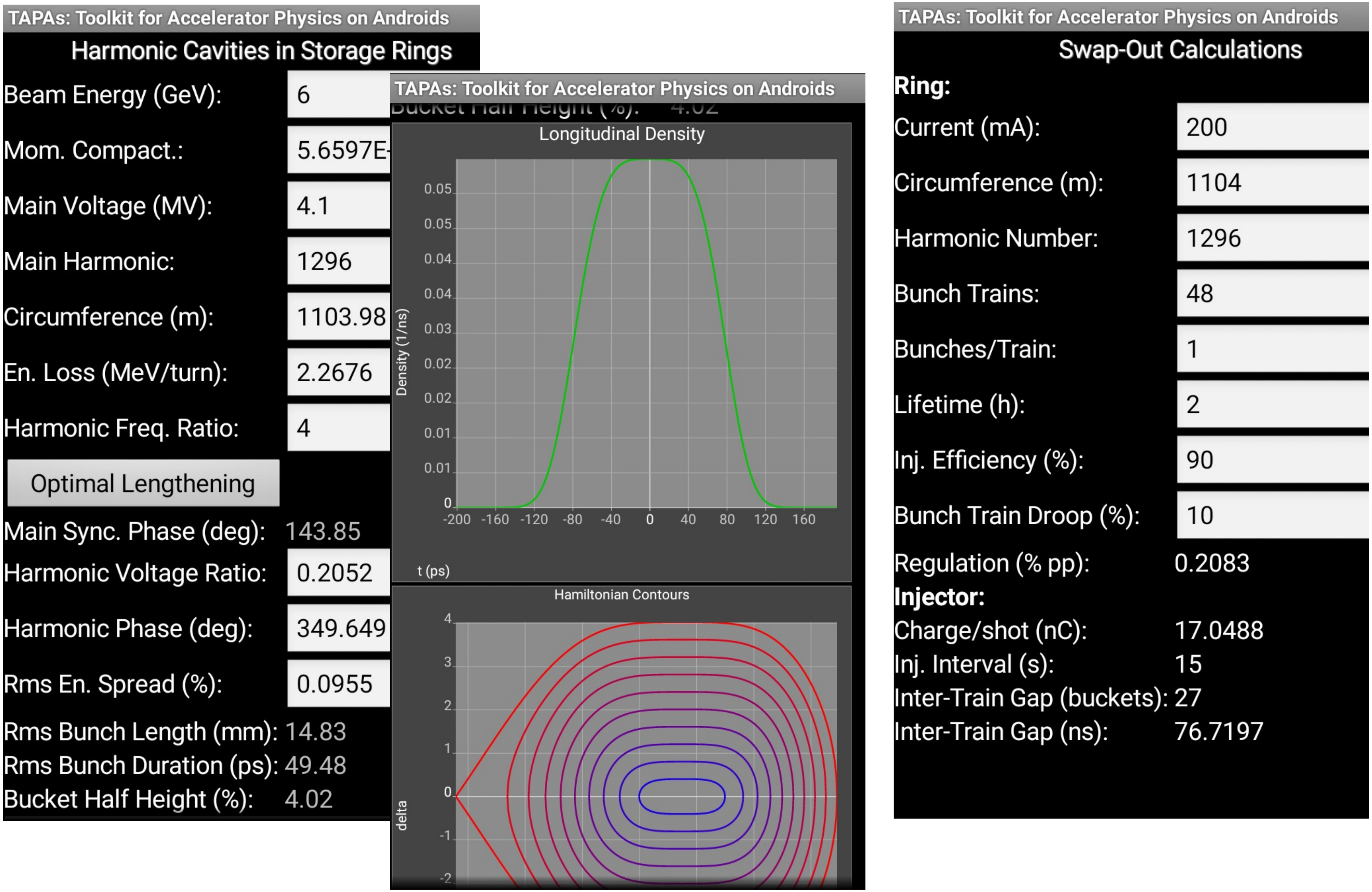


Explore MBA and HHC Physics



Screenshots from TAPAs, version 1.48, tinyurl.com/borlandTAPAs

Explore MBA and HHC Physics



Screenshots from TAPAs, version 1.48, tinyurl.com/borlandTAPAs

Conclusions

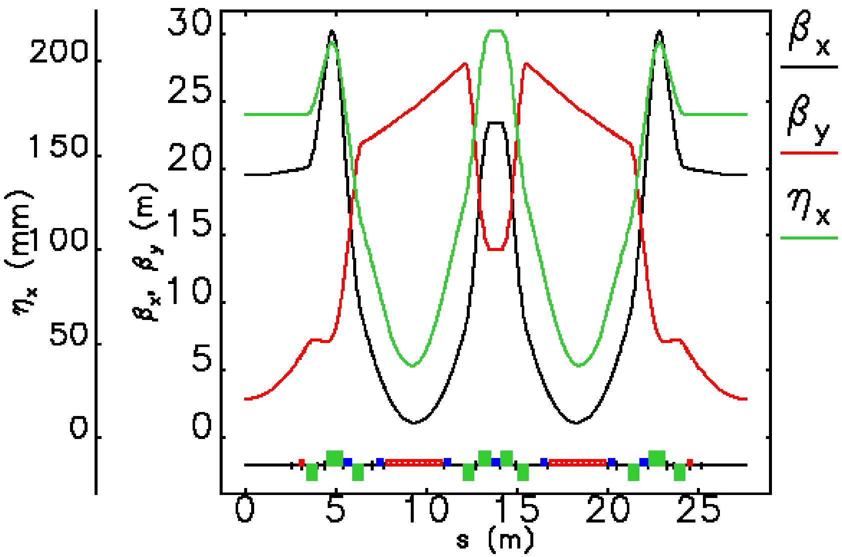
- Harmonic cavity is effective in increasing lifetime and reducing emittance
- The necessity for a bunch-lengthening cavity complicates matters for timing modes
  - 48-bunch, 200 mA mode seems workable
  - Exploring hybrid modes, other possibilities
- Extensive simulations show few issues with
  - 48-uniform, 324-uniform, 1+45, and 2x24 fill modes
  - Accidentally kicking out a bunch
  - ~10% variation in bunch-to-bunch charge
  - Rapid ID gap variation
  - Filling from zero
- Beam-phase detectors seem advisable to keep booster and ring synchronized
- May need more sophisticated system to provide users with data on bunch timing
- On-going work includes
  - Self-consistent production simulations combining IBS, HHC, and impedance
  - Use of faster rf feedback with goal of improving results for hybrid modes
  - Modeling of multi-bunch instabilities with additional cavity HOMs, longitudinal feedback
  - Add transverse impedance and verify single bunch stability limits

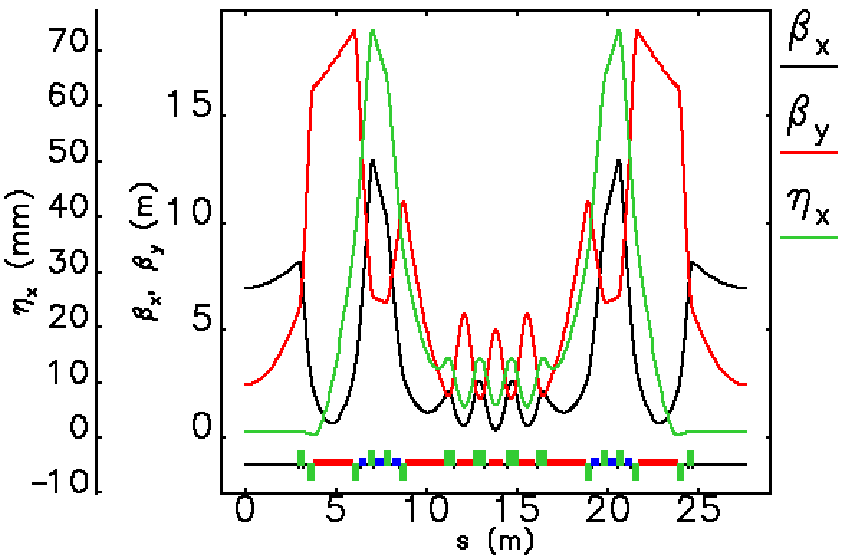
Acknowledgments

- Impedance model: R. Lindberg, A. Blednykh (BNL), Y.-C. Chae
- Error enembles for lattice evaluation: V. Sajaev
- Computing: Argonne Laboratory Computing Resources Center (LCRC)

Backup Slides

Hybrid 7BA Lattice Compared to APS Now





	APS	MBA	
Betatron motion			
ν_x	36.205	95.125	
ν_y	19.272	36.122	
$\xi_{x,nat}$	-90.340	-138.580	
$\xi_{y,nat}$	-43.319	-108.477	
Lattice functions			
Maximum β_x	30.2	12.9	m
Maximum β_y	27.8	18.9	m
Maximum η_x	0.216	0.074	m
Average β_x	13.2	4.2	m
Average β_y	15.9	7.8	m
Average η_x	0.148	0.028	m
Radiation-integral-related quantities			
Beam energy	7	6	GeV
Natural emittance	2527.5	66.9	pm
Energy spread	0.095	0.096	%
Horizontal damping time	9.7	12.1	ms
Vertical damping time	9.7	19.5	ms
Longitudinal damping time	4.8	14.1	ms
Energy loss per turn	5.34	2.27	MeV
ID Straight Sections			
β_x	19.5	7.0	m
η_x	171.88	1.11	mm
β_y	2.9	2.4	m
$\epsilon_{x,eff}$	3142.7	67.0	pm
Miscellaneous parameters			
Momentum compaction	2.84×10^{-4}	5.66×10^{-5}	
Damping partition J_x	1.00	1.61	
Damping partition J_y	1.00	1.00	
Damping partition J_δ	2.00	1.39	

H7BA lattice based on L. Farvacque *et al.*, IPAC13, 79.

Present APS fill and operating modes

- 24-bunch uniform, 100 mA
  - 75% of time
  - 6.5 MHz bunch rate
  - 120s top-up
- 324-bunch uniform, 100 mA
  - 15% of time
  - 88 MHz bunch rate
  - 12 hour "fill-on-fill" interval
- Hybrid (camshaft), 100 mA
  - 10% of time
  - One 16 mA bunch
  - 60-s top-up

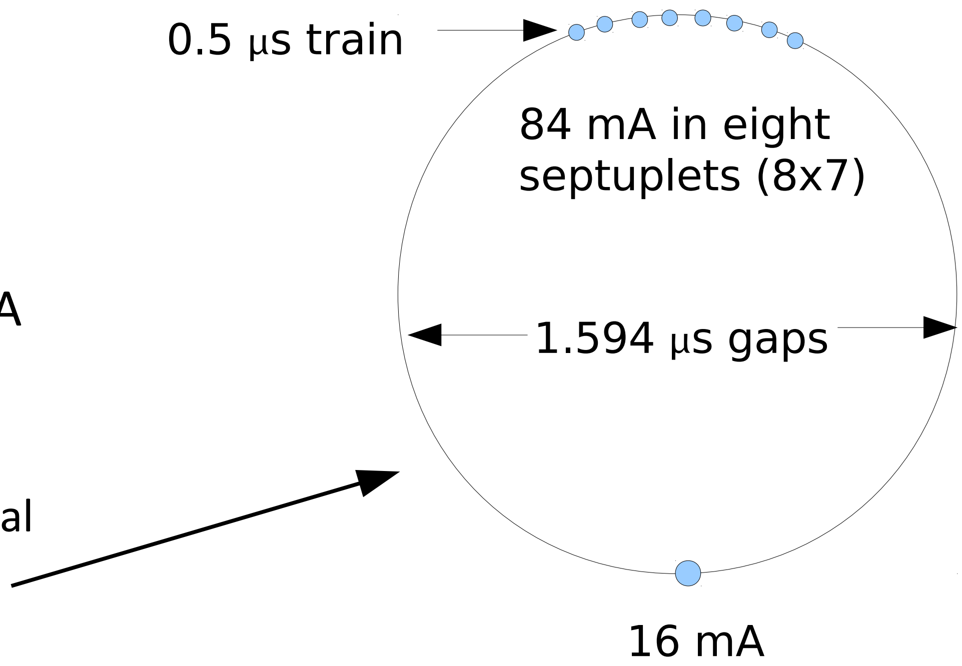
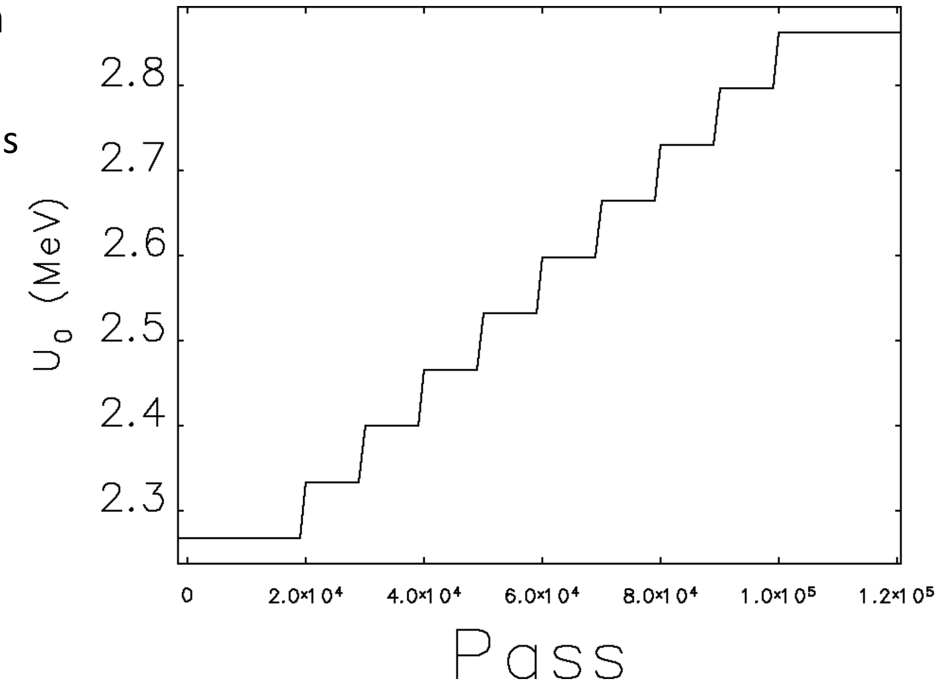


Diagram courtesy L. Emery, APS.

Effect of variation in energy loss per turn

- As ID gaps are varied, the energy loss per turn varies
  - Could vary by a significant fraction of the 2.27 MeV/turn nominal loss
  - Presently, without pre-conditioning, APS rf systems trip when closing all ID gaps rapidly
- Feedback will maintain cavity voltage and phase relative to the source, but
  - Beam will move to a different rf phase
  - Incoming bunches may suffer losses from energy oscillations due to phase offsets
  - Bunch duration will change
- Simulated unrealistically rapid variation of energy loss per turn by 0.6 MeV
  - Took 10 equal steps at 10k turn intervals
  - Ramped loss between levels over 1000 turns
  - Included effect on damping times and energy spread
  - Kept (slow) tuners for main cavities and HHC fixed



Effect of variation in energy loss per turn

- Increased energy loss moves beam higher on the main rf waveform
- Reduced slope of main rf means longer bunches
  - Good news for beam lifetime
- For 13.5 kHz bunches begin to take double-humped appearance
- Shifting phase complicates injection
  - Booster may need to track SR bucket